IMPACT VAPOR PLUME EXPANSION WITH REALISTIC GEOMETRY AND EQUATION OF STATE; H. J. Melosh and E. Pierazzo, Lunar and Planetary Lab, University of Arizona, Tucson AZ 85721-0092.

When a meteorite strikes a planetary surface at speeds greater than a few km/sec the kinetic energy of the meteorite is partially converted into heat by irreversible processes. The meteorite and some target material may vaporize after release from high pressure. In the past, a model of vapor plume expansion based on the expansion of a spherical cloud with a perfect gas equation of state was used to model the expansion of these vaporized gases [1]. However, comparison between this model and detailed numerical calculations of the Chicxulub impact [2] shows that the vapor plume in the more realistic numerical model takes far longer than predicted to accelerate out of the crater (more than 30 seconds vs. a predicted time of a few seconds). We propose that this long delay is due to a combination of the liquid-vapor phase transition in the realistic (ANEOS) equation of state used in this simulation and the non-spherical geometry of the expanding projectile. To examine these effects on plume expansion we employ a highly simplified equation of state (the Van der Waals equation) that nevertheless exhibits a liquid-vapor phase transition. Using a 1-D Lagrangian hydrocode we investigate the qualitative effect of the phase transition on vapor plume expansion and demonstrate that the expansion is affected by (1) a rapid decompression (compared to a perfect gas) that cools the supercritical rock vapor until it reaches the phase boundary followed by (2) a very slow phase of acceleration that is fueled mainly by the latent heat of the two-phase mixture. The final velocity for the realistic equation of state and a perfect gas of the same initial internal energy is nearly the same, but it takes much longer to achieve this velocity with a realistic equation of state. In addition, studies of the expansion of cylinders and planes of hot gas show that the expansion is greatly affected by the geometry of the initial gas cloud. Since an impacting projectile is quickly distorted from its initial spherical shape to a pancake-shape lining the growing crater cavity, geometric effects may also strongly affect the expansion rate. Current numerical simulations of impacts may not extend to late enough times to correctly capture the dynamics of this plume expansion and thus greatly underestimate the amount and velocity of ejected debris.

In the perfect gas model [1] the vapor accelerates to a mean velocity of $\bar{u} = \sqrt{2E}$, while the edge of the cloud reaches a speed of $u_{\max} = 2c_0/(\gamma - 1)$, where E is the specific internal energy, g is the ratio of specific heats and c_0 is the speed of sound. The gas cloud reaches this velocity in a time given roughly by R_0/c_0, where R_0 is the initial cloud radius. For the Chicxulub simulation, where the material is dunite modeled by the ANEOS equation of state [3,4], the initial radius of the projectile is 5 km, c_0= 3.3 km/sec and the expansion time is thus estimated to be 1.5 sec. On the other hand, our numerical simulation using the CSQ II hydrocode developed at Sandia National Labs indicates that tracers in the projectile are still in the floor of the crater some 40 seconds after the impact. What is the cause of this large discrepancy?

We employed the Van der Waal equation [5], $P = RT/(V-b)-a/V^2$, an analytically tractable equation of state that exhibits a liquid-vapor transition. The critical point pressure P_{crit} and temperature T_{crit} determine the constants a and b. When $a = b = 0$ the equation reduces to a perfect gas ($T_{crit} = 0$). This was coupled to a 1-D Lagrangian hydrocode especially written for this computation, but based loosely on the SALE algorithm [6]. Figure 1 shows the velocity of the outer edge of an initially 10 km diameter sphere of silicate vapor (P_{crit} = 5 GPa , T_{crit} = 15,400 K) [7] as a function of time. Its initial internal energy of 37.1 MJ/kg corresponds to an impact velocity of 20 km/sec by a fully dense (3200 kg/m^3) projectile. The same plot shows the expansion of a sphere of perfect gas with the same initial density (hence mass) and internal energy. It is readily seen that, although the two equations of state lead to nearly the same final velocity , their approach to this velocity is very different: The perfect gas expands rapidly to nearly the final velocity, while the two-phase material expands in two distinct stages. The initial rapid expansion is a result of the relatively high speed of sound of the dense supercritical fluid. However, as soon as the phase boundary is reached the expansion becomes much slower. Much of the energy is in the form of latent heat of the vapor phase which is released relatively slowly as expansion proceeds along a P-T path coinciding with the phase curve.

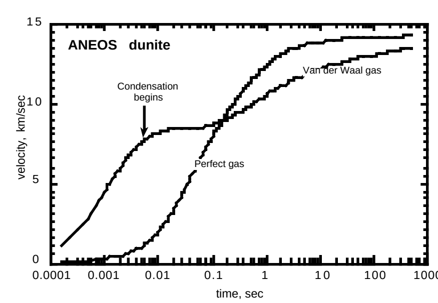
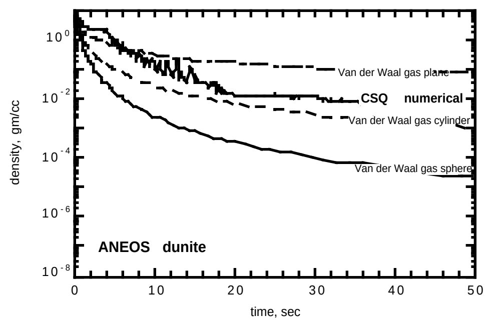


Fig 1. Expansion of a spherical cloud of a condensable gas described by a van der Waal equation of state vs. the expansion of a cloud described by a perfect gas of the same mean molecular weight. Note that the condensable gas first expands more rapidly than the perfect gas, then slows down as condensation begins. Eventually, both clouds reach nearly the same final expansion velocity.



Although the effect of the realistic liquid-vapor transition is in the right direction to explain the delay in the expansion of the vapor plume, it is not the whole effect. **Fig. 2** (above) shows the density vs. time for a tracer particle near the center of the projectile in our Chicxulub simulation for a fully dense projectile striking at 20 km/sec. Also shown is prediction of the van der Waals equation for the density at the center of a spherical cloud of condensable vapor. It is clear that the density in the Chicxulub simulation does not fall as rapidly as the spherical simulation's density. The dashed curve shows, however, the prediction for the expansion of a gas cylinder and the dot-dashed curve is for the expansion of a wide sheet of gas with the same starting conditions. The Chicxulub simulation falls approximately between these two lines (after the first few seconds that correspond to the projectile plunging into the target). It is well known from impact computations that in the early stages of crater excavation the projectile becomes greatly distorted, expanding laterally and forming a kind of liner to the growing hemispherical crater cavity [8]. Thus, its geometry is *not* close to spherical and it is perhaps unsurprising that the expansion rate is strongly affected by this geometric difference. What was not clear previously was the extent of the effect in delaying the vapor plume expansion by a factor of more than 10 times slower than expected on the basis of the simple Zel'dovich and Raizer estimate.

Conclusion: The expansion of a vapor plume from an impact takes much longer than previously used order of magnitude estimates suggest. Even though the vaporized projectile material may eventually reach very high velocities, the plume expansion time for a 10 km diameter projectile impacting the Earth is comparable to the formation time of the crater itself so that plume dynamics may need to be considered as part of the late-stage processes. This may also explain such phenomena as the late-stage melt droplet rainout of the plume observed on top of the Suevite layer at the Ries impact crater [D. Stöffler, 1996 personal communication]. It also makes the pure blast-wave approaches to atmospheric erosion via the Kompaneets solution [9] somewhat suspect.

References: [1] Y. B. Zel' dovich and Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena*, vol. 1, Academic Press (1966) [2] E. Pierazzo, H. J. Melosh and D. A. Kring, *LPSC XXVII*, pp. 1029-1030 (1996) [3] Thompson, S. L. and Lawson, H. S. Sandia report SS-RR-71 0714 (1972) [4] Melosh *et al*, in Protostars and Planets III (1993)[5] M. Planck, *Thermodynamics* 3rd ed, Dover (1952) [6] Amsden, A. A. et al., Los Alamos report LA-8095 (1980) [7] T. J. Aherens and J. D. O'Keefe, The Moon **4**, 214-249 (1972) [8] Melosh, H. J. *Impact Cratering*, Oxford (1989) [9] Newman, W. I. *et al*, 1996 preprit.